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Transactions on Emerging Telecommunications Technologies

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RESEARCH ARTICLE

Energy Optimization and Void Hole Avoidance Using Cooperative Four Hop by Hop Forwarding Verification in IoT-Enabled Underwater Wireless Sensor Network

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Received: 6 December 2024 | **Revised:** 24 November 2025 | **Accepted:** 5 April 2026

Keywords: Acoustic Sensors | Co-FHHV | Energy Efficiency | Node Discovery | Node Localization | Underwater Communication Networks

ABSTRACT

Underwater Wireless Sensor Networks (UWSNs) play a crucial role in various applications, including environmental monitoring, underwater exploration, marine communication, and disaster management. However, effective data transmission in underwater environments poses significant challenges due to high propagation delay, energy constraints, localization difficulties, and void hole issues. As the UWSN nodes are movable underwater, some of them may move far away from the relay, sensor, or sink nodes, which causes the void hole problem. Node localization with multi-hop verification cooperation can help overcome these issues. In this paper, we propose a Cooperation with Four Hop-by-Hop Forwarding Verification (Co-FHHV) scheme in UWSN to avoid the void hole and void node issues. This mechanism ensures that data moves through three intermediate relay nodes before reaching the sink node. By adding a fourth hop, each node transmits over a shorter distance, reducing energy depletion, and improving network lifetime. Each relay node performs a verification process to check for data integrity before forwarding the data. Using the localization approach to avoid the void hole is the basic motive of this article. Four verification approaches have been introduced, which utilize routing to identify the nearest nodes and activate them for communication. Each node in multiple hop-to-hop forwarding verification employs a discovery approach that attempts to avoid the void hole region and the void node. The Co-FHHV scheme employs a method to select routes with maximum residual energy and minimal hops for efficient data delivery. It also utilizes a forwarder selection strategy based on sensor priority and energy thresholds to extend the UWSN lifetime, improve energy efficiency, ensure node accurate localization, and maintain stability. The scheme used sink nodes, sensor nodes, relay nodes, and localization beacons. The proposed work is tested under multiple simulation scenarios, and the obtained results have been evaluated with the existing underwater communication schemes. The obtained results have demonstrated the excellent performance of the Co-FHHV scheme, which is considered the best among all other Schemes.

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1 | Introduction

The surveys have indicated that the Earth is covered by ~70% water [1–3]. Life in the sea is far greater than life on Earth [4–7]. Considering the communication on Earth and in the sea, it is essential to develop a communication scheme to discover life in the sea [8–10]. Various communication techniques are available that utilize specialized terminology to facilitate communication in the underwater region and with ground stations [11–14]. The Underwater Wireless Sensor Network (UWSN) is a type of sensor network that utilizes underwater communication concepts [15]. Acoustic signals are used in an underwater channel, and multiple-channel utilization techniques are employed. Sensor nodes with designations such as sink nodes, buoy, anchored nodes, relay nodes, mobile sink nodes, and acoustic signal generators are utilized in underwater communication scenarios [16–20]. The Autonomous Underwater Vehicles (AUVs) are deployed in the depths of the ocean to operate and cooperate with other nodes [21–24].

The UWSN comprises multiple nodes, each with a distinct task assigned to it. To learn about ocean life, this network can be utilized [25–30]. With the advancements and robust features in underwater communications, some limitations arise during the transmission of a data packet from the source node to the sink node and offshore station [31]. One of the major concerns and problems is the void hole and void node that occur when a data packet needs to be sent, and there is no further communication range node, or the region has no active nodes [32]. These problems result in significant packet losses and also consume more energy, as the primary nodes continue to search for the nearest possible node while using the localization scheme [33–35].

From the above-mentioned viewpoints, this article proposes a void hole and void node scheme using mobile sink and relay node localization. To operate the nodes in conjunction with other nodes, the Four Hop by Hop Verification (FHHV) scheme has been introduced, leveraging the cooperation of the mobile sink and relay nodes. This scheme employs four alternative solutions to identify the new possible node, utilizing the four RREQ (Route Request) and RREP (Route Reply) mechanisms. Each node searches for the nearest possible node while updating its routing table entries. At the end of the searching process, each node updates the table and thus originates the routing path, where possible, for active nodes to send data packets.

The movement of nodes in UWSNs can lead to unreliable communication paths and inefficient data forwarding. Co-FHHV enhances forwarding strategies through cooperative four-hop verification to address dynamic node mobility. Due to limited energy resources in underwater sensor nodes, energy-efficient communication strategies are crucial. The Co-FHHV scheme optimizes energy consumption by minimizing unnecessary transmissions and improving data forwarding efficiency. Void holes in UWSNs, caused by the absence of active nodes in certain regions, disrupt the communication process. Co-FHHV mitigates this issue by utilizing cooperative forwarding techniques to avoid void holes and ensure reliable data transmission. These challenges are central to the design of the Co-FHHV scheme, which aims to enhance network performance, reliability, and energy efficiency in UWSNs, particularly in dynamic and resource-constrained underwater environments. The Co-FHHV scheme presents a robust and energy-efficient method for data transmission in UWSNs by integrating cooperative multi-hop forwarding, localization support, and verification mechanisms. By ensuring that the sink node remains at the surface for data aggregation, while sensor and relay nodes operate efficiently at lower depths, the proposed approach maximizes network performance, energy efficiency, and reliability. Localization beacons further enhance the scheme by enabling precise positioning, which is critical for optimal routing and communication. As underwater communication continues to evolve Co-FHHV sets a strong foundation for future enhancements in secure, scalable, and energy-efficient underwater sensor networks. The end-to-end communication scenario of Co-FHHV in UWSN is illustrated in Figure 1. End-to-End communication scenario of Co-FHHV in UWSN. The primary contributions are as follows:

- We propose a Co-FHHV scheme to enhance energy efficiency in underwater communication by addressing void hole problems through cooperation. It focuses on optimizing energy and channel efficiency by utilizing sink and relay node localization techniques and increasing the number of sink nodes to enhance communication stability and reduce broken paths.
- The primary objective is to ensure maximum communication efficiency for both underwater and water surface sensor nodes. The scheme focuses on optimizing communication for both underwater and surface nodes, increasing the number of sink nodes to enhance communication reliability with the base station.

This paper is organized as follows: Section 1: Introduction, Section 2: Related Work, Section 3: Research Methodology, Section 4: Results and Discussion, Section 5: Conclusion.

2 | Related Work

Authors in [36] proposed a UWSN communication scheme focused on energy optimization and energy consumption. The authors have also used propagation models for acoustic communication underwater. Their study revealed that energy consumption and the delay in delivery ratio have a significant impact on the performance of UWSN. Likewise, authors in [37] stated that they had proposed a new routing approach for enhancing the performance of UWSN communication, and for this, they had addressed security issues in the routing. Different security attacks were tested and introduced. Their primary concern was routing with security to ensure secure communication. Authors in [38] improved the Quality of Services (QoSs) by proposing a hybrid approach for UWSN. They had proposed the scheme of signal amplification to utilize the best and boost the acoustic signal. With the implementation of 5G, their study has achieved outstanding performance. Authors in [39] to boost the signal for both the acoustic and the offshore control station with the IEEE standards of 802.11 s, the authors have proposed their work by focusing on this. With the new IEEE standard, which works on the surface like Earth and terrestrial sensor networks, the authors

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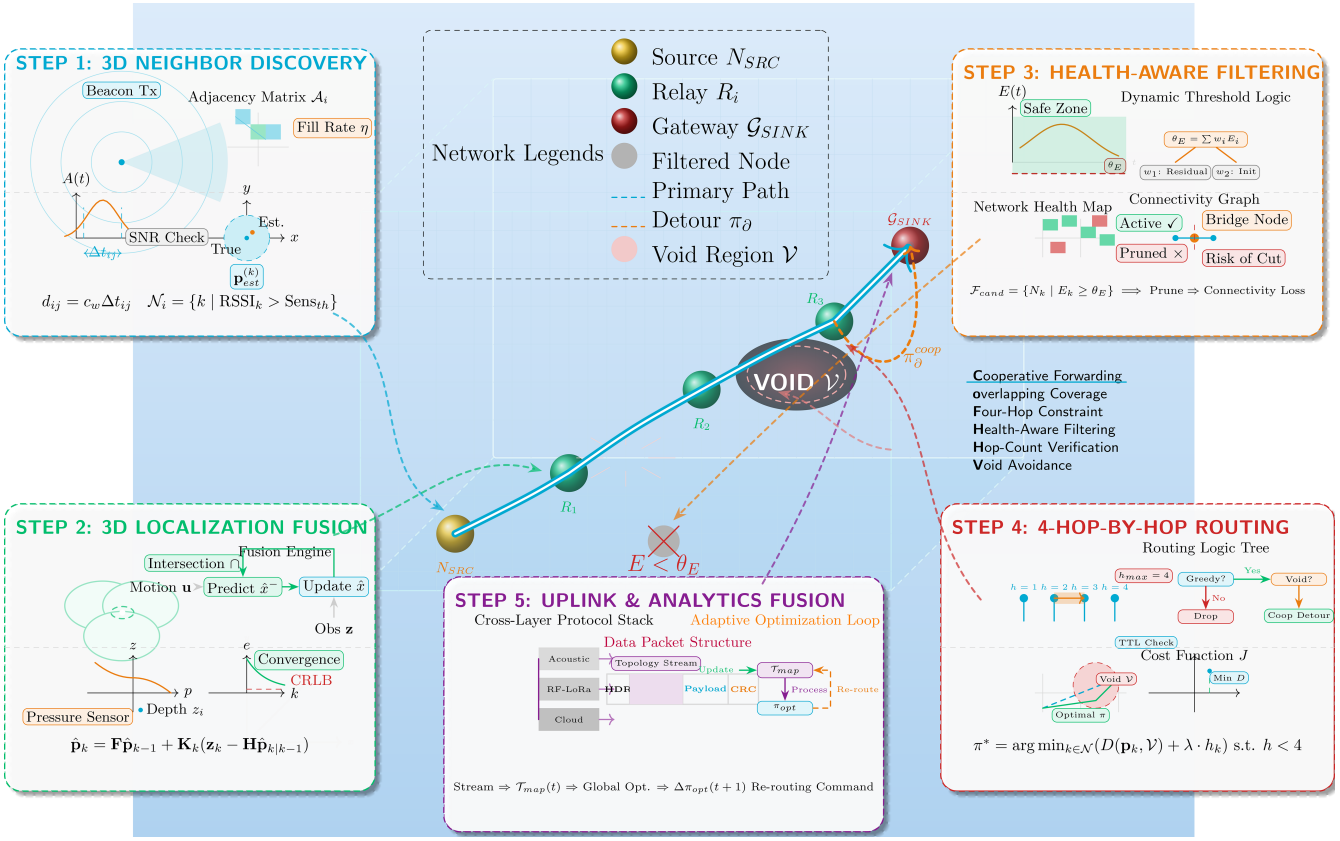


FIGURE 1 | End-to-End Communication Scenario of Co-FHHV in UWSN.

have employed two terminologies. One for the acoustic signal amplification, which boosts the signal with advancements in the relay and movable sink nodes. Additionally, the other goal was to enhance the signal amplification of the terrestrial and water surface nodes. From their simulation results, it was concluded that the signal amplification has a huge impact on both underwater and terrestrial sensors. Authors in [40] have proposed a verification scheme with a forwarding mechanism to avoid void holes and void nodes. They have used two hop-by-hop verifications, which were based on the forwarding approach in UWSN. They have used the delay of propagation, the delivery ratio, and most importantly, the lifetime and energy consumption of the network as their core metrics. From multiple scenarios of the results, it has been proven that void hole avoidance can still be further improved by using more hop-by-hop schemes. Authors in [41] stated that they aim to avoid the void hole and propose a scheme that consumes a lower amount of energy. Thus, from this viewpoint, the authors have proposed a novel approach for avoiding the void hole. Furthermore, they had also introduced the node localization scheme to avoid the void node. The void node is a scenario when there are no further communication nodes available in the range of the previous sensor node. Authors in [42] proposed a new link stability metric for UWSN that utilizes a threshold estimation scheme. The link stability was performed by the safety degree of mobility, the prediction factor of mobility, and the movement of the relay and sink nodes. The threshold values were introduced to maintain link stability, thereby avoiding both path loss and transmission loss. Authors in [43] have proposed a routing scheme named Neighboring-Based Energy Efficient Routing (NBEER) with the proper implementations of the nearby nodes. The NBEER can maintain the number of sensor nodes with the minimum distances from each other. The core idea of this protocol was to develop a scenario in which each node discovers the nearest possible node for communication, and to check its energy level and path loss avoidance. Authors in [44] have introduced a novel routing technique called Cooperative-Relay Neighboring-Based Energy-Efficient Routing (CR-NBEER). The CR-NBEER was developed for signal boosting and to maintain the minimum communication distances. The authors have used the relay optimization schemes with improvements in the sink nodes. Both the movable relay and movable sink nodes, with the proper implementations, were taken into consideration. The results of this scheme were evaluated in comparison to other existing approaches for UWSN. From the results, it was shown that increasing the number of sink and relay nodes can ultimately enhance and improve the signal and performance of underwater communications. Recent studies have significantly advanced the fields of underwater communication, robotics, and control systems. Authors of [45] proposed an energy-efficient, trust-based AUV scheme for 6G-enabled IoUT, improving autonomous underwater vehicle communication and energy management. In the same year, they also addressed void hole avoidance in [46], enhancing data transmission reliability. Authors in [47] developed a distributed and parallel accelerator architecture for 3-D acoustic imaging using FPGA-based systems, enhancing computational efficiency and scalability in acoustic signal processing. Authors in [48] combined inertial measurement unit (IMU) data with acoustic sensing to achieve precise head motion tracking via wireless earphones, thereby improving motion-aware mobile computing. Authors in [49] proposed

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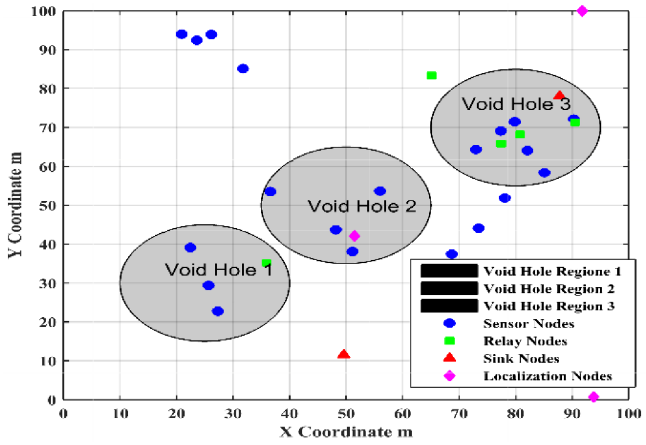


FIGURE 2 | Proposed FHHV for void hole and void node avoidance.

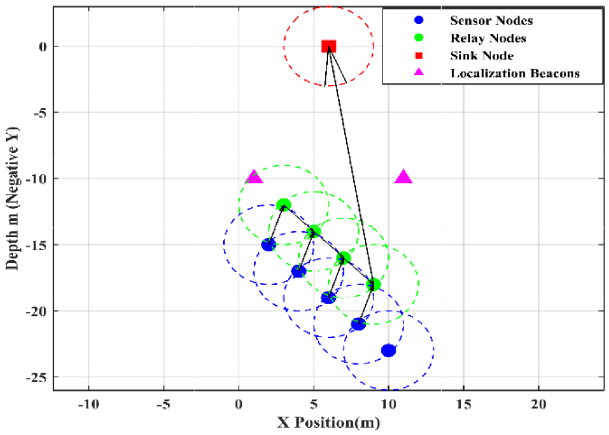


FIGURE 3 | Illustration of hop-by-hop forwarding.

a UAV-relay-aided secure maritime communication framework integrating satellite networks, featuring robust beamforming and trajectory optimization for reliable and secure data transmission. Authors in [50] introduced GENDN, a geospatially enhanced Named Data Networking (NDN) framework, designed for efficient location-based publish/subscribe services in non-terrestrial network (NTN)-enabled IoT environments. Authors of [51] presented an adaptive sliding mode approach for tracking heterogeneous underwater vehicles, thereby improving synchronization and robustness in uncertain conditions. These works collectively push the boundaries of underwater technologies, addressing challenges in communication, imaging, and robotics.

3 | Methodology

The proposed methodology comprises multiple stages, each representing a distinct approach. The problem identification and its solutions are also proposed, which is an obligatory task for the concerned study. It is a major concern to design the work diagram and its equivalent features that follow. The methodology is further explained as follows:

3.1 | Problem Identification

The proposed work focuses solely on avoiding void holes and void nodes that occur in the void region. By doing so, there are four possible combinations and possibilities for achieving the proposed work. Figure 2 illustrates the void hole problem, showing the void region and its avoidance by using an alternative path. Four node verification schemes are introduced, which focus on void hole and void node avoidance. When a node sends a packet to another node, and there is no further active node within the range of the source node. Then, that node tries to discover the nearest possible nodes by using the FHHV schemes.

Hop-by-Hop Forwarding is a routing technique where data is forwarded from one node to another, with each intermediate node acting as a relay. This method involves a step-by-step transmission of data through several nodes in the network until it reaches the destination. Each node forwards data only to its immediate neighbor, thereby reducing complexity and energy consumption at each stage. The 2-hop forwarding involves sending data through two intermediate nodes before it reaches the destination. This can help reduce transmission delays and energy consumption compared to longer hop counts, though it may increase the potential for interference and path loss. Similarly, in 3-hop forwarding, data passes through three intermediate nodes. This extended forwarding path can help mitigate the impact of void holes (regions without coverage) and improve network robustness. However, it might incur more energy consumption due to additional relay steps. The proposed scheme employs four-hop-by-hop forwarding in every communication scenario. The 4-hop forwarding involves four intermediate nodes, offering a more reliable path for data transmission, especially in networks with void holes or large areas. It helps avoid coverage gaps and improves localization accuracy. Each increase in hop count improves the network's ability to handle void regions and enhance localization accuracy. Figure 3 illustrates the hop-by-hop forwarding, and Figure 4 illustrates the 2-hop, 3-hop, and 4-hop forwarding scenarios.

3.2 | Proposed Co-FHHV Scheme

The FHHV schemes are introduced, which is the major concern of this article. Figure 5 illustrates the overall structure and methodology of the proposed scheme, which utilizes multiple FHHVs to avoid the void hole and transmit data packets via an appropriate route. At the initial state, the neighbor request packet phase occurs during communication. If the response is affirmative, the method proceeds to update the table for the neighbor node. If not, it reverses the process and starts from the beginning. Moving on to the next phase, the data packet is ready to be sent further, and it is here that the FHHV schemes are utilized. Each HHV uses the conditional statements to fetch the hop information. At the last stage, the conditions are evaluated by focusing on whether the node is void, allowing the packet to drop, or if not, then transferring the packet forward.

3.3 | Proposed FHHV Scheme With Cooperation Approach

The cooperation scheme has been implemented and introduced in conjunction with the proposed FHHV schemes. The FHHV

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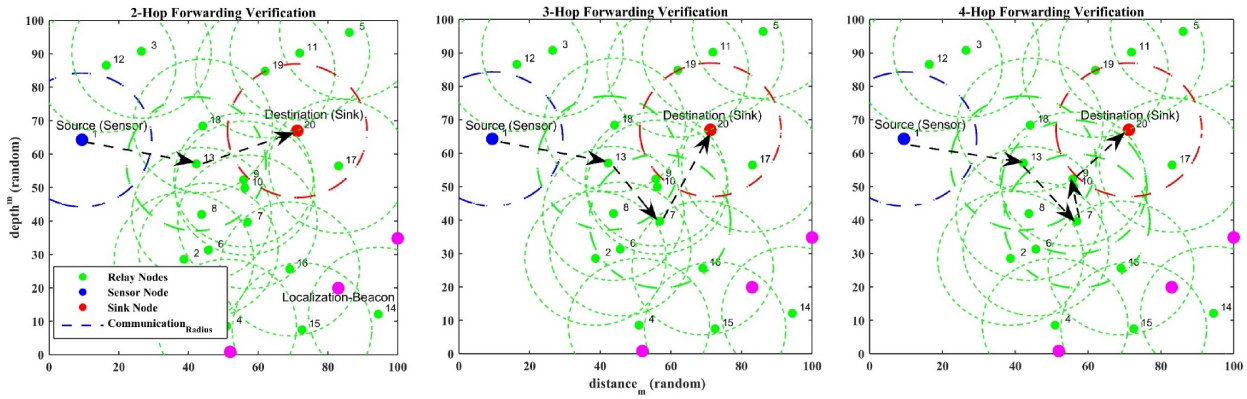


FIGURE 4 | Illustration of two, three, and four hop-by-hop forwarding.

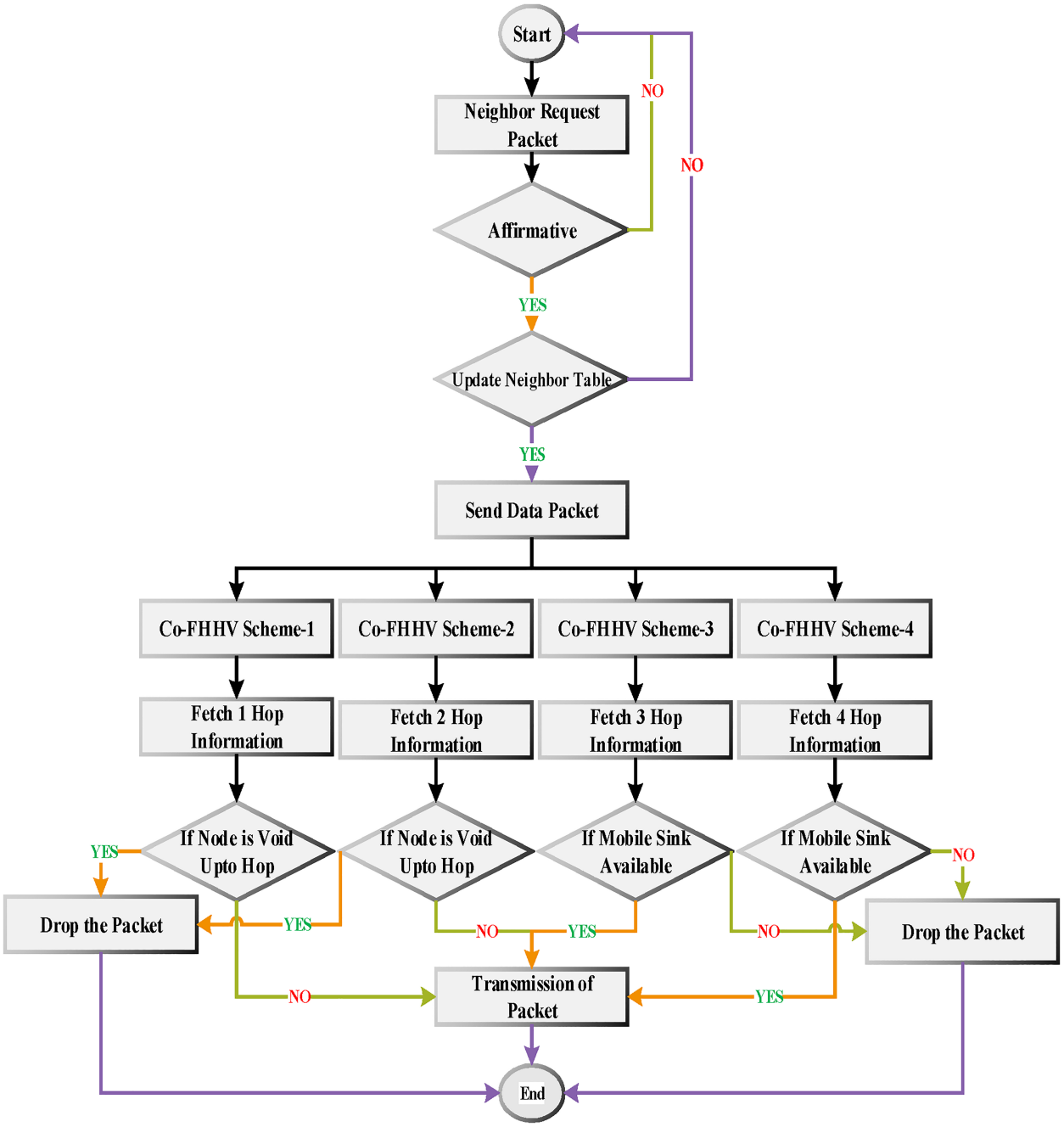


FIGURE 5 | Deployment of the FHHV schemes with forwarding verifications.

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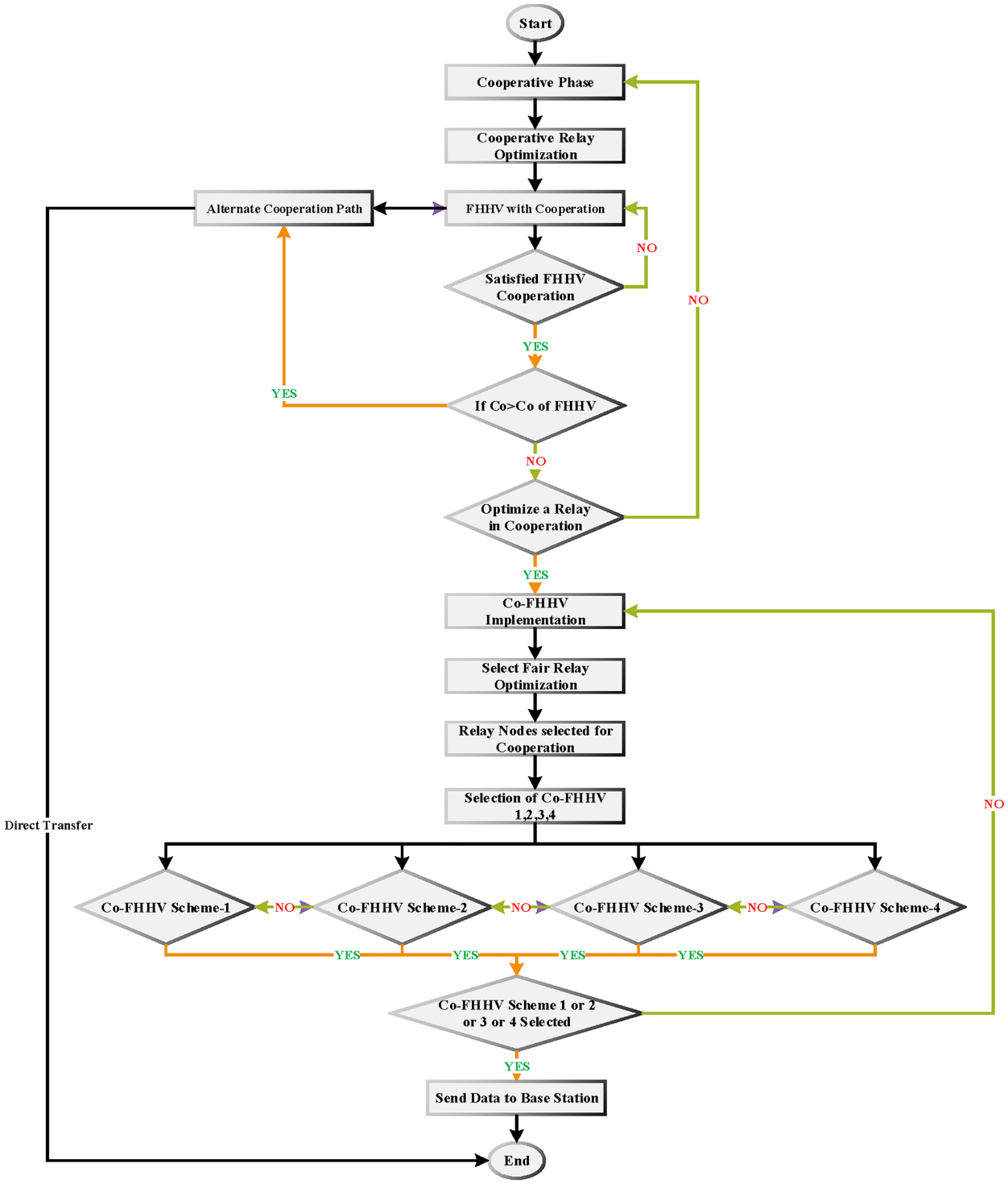


FIGURE 6 | Method of the FHHV schemes with cooperation approach.

scheme utilizes node and route discovery, whereas the cooperation scheme employs relay and sink mobility nodes to enhance signal and network performance. Figure 6 illustrates the proposed FHHV scheme with the deployment of the cooperation approach. When a node satisfies the condition that there exists another node for communication, the FHHV scheme uses an alternate path to maintain communication, utilizing advanced relay nodes to avoid the void hole with the relay localization approach.

The Four-Hop by Hop Forwarding Verification (FHHV) algorithm, as shown in Figure 5, and the Co-FHHV data forwarding scheme, depicted in Figure 6, in UWSNs are interconnected concepts that address key issues in efficient data transmission, particularly in challenging environments such as void holes and regions with limited or no connectivity. The Co-FHHV algorithm enhances the basic FHHV concept by incorporating multiple nodes to verify and forward data in a more coordinated manner, overcoming the challenge of void regions and connectivity gaps.

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In the Co-FHHV scheme, four nodes are defined as FHHV-1, FHHV-2, FHHV-3, and FHHV-4. These nodes play crucial roles in the forwarding verification process. The role of these nodes is to ensure data is forwarded from one node to another, with each hop being validated. The algorithm first checks if the current node is within a void region. If the node is in a void, it halts the beacon message to avoid unnecessary data transmission that won't reach the intended destination. This process helps prevent wasted energy and ensures the system remains efficient. The algorithm checks for neighboring nodes and identifies the set of void region nodes. If the current node is within a void region (a region with no nearby nodes to forward data), it sets up a verification step to ensure proper data transmission through alternative paths or node redeployment. The FHHV process plays a critical role in ensuring data is forwarded across multiple hops, especially in regions where traditional single-hop or direct communication methods fail due to the presence of voids. Here's how the connection works:

If the current node is identified as being part of a void region, the algorithm initiates a re-evaluation of the node's position, enhancing the transmission radius by adjusting the localization parameters. This ensures the node can communicate with other nodes even if it's near or within a void region. The algorithm calculates the Euclidean distance between nodes using the formula: $FHHV = \sqrt{(A - B) + (C - D)}$ Here, A, B, C, and D are the positions or identifiers of the nodes, and the FHHV calculation ensures that the nodes are within a reachable distance. If the calculated derivative distance is smaller than the existing FHHV, the forwarding path is adjusted accordingly. The algorithm continues by calculating the derivative between node pairs and comparing this to the expected FHHV values. Suppose the distance is acceptable (i.e., derivate < FHHV), it means that the path is valid and data forwarding can proceed. However, if the calculated derivative exceeds the threshold, the algorithm forces the forwarding process to check alternative nodes or increase the number of hops to ensure data reaches the destination. If the node's position or connectivity remains insufficient to avoid voids, the algorithm relocates the node to a new region, improving the likelihood of finding valid forwarding nodes. This reconfiguration helps avoid the void hole issue by optimizing node placement and adjusting the forwarding paths. The Co-FHHV data forwarding scheme integrates FHHV verification into a larger, more robust system for data transmission in UWSNs. While FHHV addresses local forwarding and path validation in real-time Co-FHHV provides an overarching framework that manages node deployments, recalculates transmission paths, and effectively avoids void regions. This ensures that even in challenging conditions, such as underwater environments where communication paths can be disrupted, the system remains adaptive, efficient, and capable of reliable data delivery. By combining these processes, the Co-FHHV scheme enables the network to dynamically adjust to environmental changes, such as void regions, and optimize node communication to maintain the integrity of data transmission in UWSNs. The pseudo-code of the proposed work is presented in Algorithm 1, which includes four HHVs and their respective deployments to avoid void holes and void nodes. The simulation setup, including each parameter and its details, is presented in Table 1.

ALGORITHM 1 | Void hole avoidance using FHH forwarding verifications.

1. Inputs: Network graph G = (V, E), sink s, max hops H = 4, parameters Emax, Eth, Dmax, α, β, γ
2. Outputs: Forwarding path(s), updated energies, void-hole decisions
3. Initialize and Seed
4. For each node i ∈ V: set Ei_initial = Emax; discover neighbors within Dmax
5. Per Round Loop (for each simulation round r)
6. For each source node u with data
7. Hop counter h ← 0; current node c ← u; path Π ← [u].
8. While c ≠ s and h < H:
9. Void Detection/Marking
10. Compute VHR_c using Equation (5) with Dmax and Eth.
11. If VHR_c = 1: attempt local detour (neighbor with VHR = 0); if none, mark c as void node and abort this flow.
12. Neighbor Scoring for Forwarding Candidates.
13. For each neighbor j of c with VHR_j = 0:
14. Estimate Tx energy Ec to j via Equation (1); update Ec_res via Equation (2).
15. Compute cooperative forwarding weight Pj via Equation (3) using Ej_res and distance to sink.
16. Compute forwardability contribution (1 − VHR_j) for hop h + 1 as in Equation (6).
17. Compute verification score for hop c → j: Pverif,j via Equation (7).
18. Compute energy-aware metric (EAVHM, MHFO) and apply penalty (VHEP) as per Equations (8), (18), and (19).
19. FHHV Selection — Four Hop-by-Hop Verification.
20. Aggregate a composite score for each j:
21. Sj = Pj × Pverif,j × (1 − VHR_j) × EAVHM_j × MHFO_j ÷ VHEP_j.
22. Select next hop c* = arg max_j Sj.
23. Commit transmission c → c*: update energies and append c* to Π; set c ← c*; increment h.
24. 2.3 If c ≠ s after H hops: declare void-induced failure for this packet; update void statistics.
25. Post-Round Metrics and Bookkeeping
26. Route discovery quality via Equation (4) over realized hops on Π.
27. Path reliability Rpath via Equation (15) using actual Pverif and per-hop Pfwd (from Equation (6)).
28. Cooperative energy CECM via Equation (17); hop energy efficiency HBEh via Equation (12).
29. Void statistics: VHRF via Equation (11); penalty audit via Equation (14).
30. Distance-based allocation check via Equation (16) for fairness on long links.
31. End-of-Simulation Outputs.
32. Energy efficiency ηnet via Equation (10); network lifetime Lnet via Equation (9).
33. Optimization summary consistent with Equation (20) (PONL).

3.4 | Proposed System's Mathematical Model

The proposed model involves energy optimization through cooperative data forwarding, void hole avoidance, and multi-hop forwarding using a Hop-by-Hop Verification technique. The system's operation can be defined using several interrelated mathematical formulations that incorporate energy levels, hop

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TABLE 1 | Simulation setup and basic assumptions.

Parameter(s)	Value(s)
System information	RAM: 8GB, Processor: Intel Core i3, 2310 M 2.5GHz (4 CPUs), Operating System: Windows 10
Simulation tool	MATLAB R2024a
Total nodes	50 (randomly deployed)
Mobility model	Random Waypoint, Gauss Markov
Nodes primary/max energy level	12 joules
Sensor nodes transmission radius	160 m
Network volume	$1000 \times 800 \times 500 m^3$
Acoustic frequency	1500 m/s
Packets size	1024-bits
Simulation time	1000 Rounds
Proposed scheme	Co-FHHV
Random seed initialization	Fixed seed (e.g., rng(42))
Simulation repetitions	Each experiment was repeated 10 times; the results were averaged
Variance/error measure	Standard deviation and 95% confidence intervals reported

counts, forwarding verification, and localization. Given Parameters, Max Energy per Node: Emax = 12 J, Simulation Rounds: $R = 0{:}100{:}1000$, Total Nodes: $N = 50$, Hop Count: H = 4 (4-hop transmission with 1 sensor, 3 relay nodes, and 1 sink node), Packet Size: b = 1024bits, Distance per Hop: d = 160 m, Transmission Energy per Node: Etx = 5.2512 mJ, and Reception Energy per Node: Erx = 51.2 μJ.

3.4.1 | Energy Consumption and Transmission Power

Energy consumption is directly proportional to the transmission power required to send data over a distance. The energy consumed by node i during a data transmission is given by:

$$E_i = P_{trans} \cdot d_{ij}^{\alpha} \cdot T_i \tag{1}$$

where P_{trans} is the transmission power in watts, d_{ij}^{α} is the distance between node i and node j, A is the path loss exponent (typically 2 for free space), and T_i is the transmission time required to send a message from node i to the next node.

3.4.2 | Residual Energy of Node i

The residual energy E_i^{res} of a node i after transmission is given by;

$$E_i^{res} = E_i^{initial} - E_i \tag{2}$$

where $E_i^{initial}$ is the initial energy of node i, and E_i is the energy consumed during transmission.

3.4.3 | Cooperative Forwarding With Energy Efficiency (CFE)

The cooperative forwarding probability P_i is proportional to the residual energy of node i and its distance from the sink node. This can be mathematically represented as;

$$P_i = \frac{E_i^{res}}{d_i^{\beta}} \tag{3}$$

where E_i^{res} is the residual energy of node i, d_i is the distance of node i from the sink, and β is a weight factor that balances energy and distance considerations.

3.4.4 | Route Discovery With Multi-Hop Verification (RD-MHV)

In this step, nodes perform a route discovery based on residual energy and stability. The route selection probability is defined as follows:

$$P_{route} = \prod_{i=1}^{N} \left(\frac{E_i^{res}}{H_i} \right) \tag{4}$$

where N is the number of hops in the selected route, E_i^{res} is the residual energy of node i, and H_i is the hop count for the route. The objective is to select the path that minimizes the total energy consumption and hop count.

3.4.5 | Void Hole Detection and Avoidance (VHDA)

To avoid data forwarding through void holes, the following equation evaluates the Void Hole Region (VHR) based on distance and energy constraints:

$$VHR = \sum_{i=1}^{N} \left(d_{ij} > D_{\max} \right) \cdot \left(E_i^{res} < E_{th} \right) \tag{5}$$

where d_{ij} is the distance between nodes i and j, $D_{\max}$ is the maximum allowable transmission distance, and E_{th} is the energy threshold at which the node begins to forward data. Nodes that meet both conditions are classified as being within a void hole region.

3.4.6 | Multi-Hop Data Forwarding With Void Hole Avoidance (MHDF-VHA)

Multi-hop data forwarding is performed using neighboring nodes that are not in the void hole region. The forwarding probability is given by:

$$P_{fwd} = \prod_{i=1}^{H} \left(1 - VHR_i\right) \tag{6}$$

where VHR_i is the void hole region detection for hop i, and H is the number of hops in the path.

3.4.7 | Cooperative Verification for Hop-By-Hop Forwarding (CV-HHF)

Each node i verifies the availability of the next hop based on its energy and the stability of the forwarding link. The probability of

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a successful hop verification is:

$$P_{verif} = \frac{E_i^{res}}{d_i^{\gamma}} + 1 \tag{7}$$

where γ is a factor indicating the weight of distance on verification, and E_i^{res} is the residual energy of node i.

The energy consumption model used in our system is based on established principles of energy consumption for UWSNs. It accounts for factors such as transmission power, transmission duration, and path loss. The model assumes that energy consumption is directly proportional to the distance between nodes and the required transmission power, with additional considerations for energy losses during acoustic wave propagation. The equations for cooperative data forwarding were derived based on the assumption that nodes with sufficient residual energy and proximity to the sink node will participate in forwarding data. The model aims to minimize energy consumption while ensuring reliable packet delivery, efficient node localization, and avoiding void hole issues. The forwarding probability is computed using the energy levels and distances of nodes, optimizing the selection of nodes that are energy-efficient for data transmission. The void hole avoidance mechanism is derived based on the assumption that if a node's residual energy is too low or it is located in a region where no other node can serve as a next hop, it will be excluded from the forwarding process. This ensures that data is routed through reliable and energy-efficient nodes. The algorithm dynamically detects void holes and adjusts the routing path to avoid energy-depleted nodes or regions.

The mobility model assumes that nodes move within a given area at a predefined speed and along a predefined trajectory. This model is crucial for determining the expected distance between nodes at any given time, which impacts both energy consumption and the likelihood of successful data forwarding. The mobility model influences routing decisions, particularly when nodes are distant from each other or encounter network partitioning. The integration of Gauss-Markov and random mobility models in Co-FHHV for UWSNs is a practical approach to simulate real-world scenarios and test the performance of the protocol under different movement patterns. This integration helped refine routing strategies, improve forwarding efficiency, and assess the protocol's adaptability in dynamic UWSNs environments.

3.4.8 | Energy-Aware Void Hole Mitigation (EAVHM)

The energy-aware strategy aims to select paths with minimal energy consumption, avoiding void hole regions. The energy-aware path selection equation is:

$$P_{EAVHM} = \sum_{i=1}^{N} \left(\frac{E_i^{res}}{H_i \cdot d_{ij}} \right) \tag{8}$$

where H_i is the hop count for node i, and d_{ij} is the distance between node i and its neighbor node j. This equation selects the path with minimal energy consumption and avoids void holes.

3.4.9 | Network Lifetime Estimation (NLE)

The network lifetime L_{net} is the time duration until the first node runs out of energy. It can be calculated as;

$$L_{net} = \frac{E_{min}}{P_{avg}} \tag{9}$$

where E_{min} is the minimum residual energy among all nodes, and P_{avg} is the average power consumption for all nodes.

3.4.10 | Energy Efficiency of the Network (EEN)

Energy efficiency η_{net} is calculated as the ratio of successfully forwarded packets to the total energy consumed;

$$\eta_{net} = \frac{\sum_{i=1}^{N} Packets_{fwd}}{\sum_{i=1}^{N} E_i} \tag{10}$$

where $Packets_{fwd}$ is the number of successfully forwarded packets by node i, and E_i is the energy consumption of node i.

3.4.11 | Void Hole Reduction Factor (VHRF)

The VHRF is the percentage reduction in void hole occurrences after the avoidance algorithm is applied.

$$VHRF = \frac{\sum_{i=1}^{N} \left(VHR_i^{pre} - VHR_i^{post} \right)}{VHR_i^{pre}} \times 100 \tag{11}$$

where VHR_i^{pre} is the void hole region occurrence before mitigation, and VHR_i^{post} is the occurrence of void hole regions after mitigation.

3.4.12 | Hop-Based Energy Optimization (HBE)

The HBE for each transmission hop h is calculated as follows:

$$HBE_h = \frac{E_h^{trans}}{P_h} \tag{12}$$

where E_h^{trans} is the energy consumed at hop h, and P_h is the power required for transmission at hop h.

3.4.13 | Void Hole Awareness via Cooperative Nodes (VHA-CN)

The cooperative nodes, during data forwarding, mitigate the impact of void holes by verifying the energy status of the next hop. The probability of successful forwarding with cooperative verification is given as follows:

$$P_{success} = \prod_{i=1}^{N} \left(1 - \left(VHR_i \cdot V_i\right)\right) \tag{13}$$

where VHR_i is the void hole region, and V_i is the verification successful at node i.

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3.4.14 | Void Hole and Energy Depletion Avoidance (VHEDA)

To further enhance void hole avoidance, we can introduce a penalty function for paths that cross energy-depleted nodes, which is given as follows:

$$VHEDA = \sum_{i=1}^{N} \left(\frac{1}{E_i^{res}} \right) \cdot \left(1 - VHR_i \right) \tag{14}$$

where E_i^{res} is the residual energy, and VHR_i is the void hole region at node i.

3.4.15 | Path Stability and Reliability Metric (PSRM)

Path stability is critical in multi-hop forwarding. The reliability R_{path} of a path can be expressed as;

$$R_{path} = \prod_{i=1}^{N} \left(P_{verif} \cdot P_{fwd} \right) \tag{15}$$

where P_{verif} is the hop verification probability, and P_{fwd} is the forwarding probability.

3.4.16 | Distance-Based Energy Allocation (DBEA)

The energy allocated to each hop is inversely proportional to the distance between nodes.

$$DBEA = \frac{E_{allocated}}{d_{ij}} \tag{16}$$

where $E_{allocated}$ is the energy allocated for transmission (12j is set the max E/node), and d_{ij} is the distance between nodes i and j.

3.4.17 | Cooperative Energy Consumption Metric (CECM)

The total energy consumed for cooperative data forwarding is given by:

$$CECM = \sum_{i=1}^{N} \left(E_i^{trans} + E_i^{coop} \right) \tag{17}$$

where E_i^{trans} is the energy consumed in transmission, E_i^{coop} is the energy consumed in cooperation.

3.4.18 | Multi-Hop Forwarding Optimization (MHFO)

The optimization of multi-hop forwarding, considering both energy consumption and void hole avoidance, is given by:

$$MHFO = \sum_{i=1}^{N} \left(\frac{E_i^{res}}{d_{ij} \cdot H_i} \right) \tag{18}$$

where E_i^{res} is the residual energy, and H_i is the hop count.

3.4.19 | Void Hole and Energy Penalty (VHEP)

A penalty function for paths encountering void hole regions is given by:

$$VHEP = \sum_{i=1}^{N} \left(\left(VHR_i \cdot P_{fwd} \right) + \frac{1}{E_i^{res}} \right) \tag{19}$$

where VHR_i is the void hole region, P_{fwd} is the forwarding probability, and E_i^{res} is the residual energy.

3.4.20 | Path Optimization for Network Lifetime (PONL)

Finally, the network lifetime optimization with path selection and energy awareness is given by:

$$PONL = \max \left(\sum_{i=1}^{N} \frac{E_i^{res}}{d_{ij} \cdot P_{fwd}} \right) \tag{20}$$

where E_i^{res} is the residual energy, d_{ij} is the distance between node i and node j, and P_{fwd} is the forwarding probability.

4 | Results and Discussion

The results of different evaluation parameters are evaluated and discussed in this section. Each parameter has been given full attention and has been contrasted with the proposed Co-FHHV scheme. The four major possibilities have been countermeasured. The four proposed parameters, along with graphical and tabular explanations, are presented below.

4.1 | End-To-End Delay (EtED) Analysis

The primary focus is to analyze the EtED and compare the performance of the proposed scheme with that of existing ones. Here, the delay is measured in milliseconds, and each time slot indicates a different EtED with 100 rounds of simulation. The overall simulations were executed for 100 s, divided into 10-s intervals. The 0-s values are also indicated, which denote the primary and initial system configuration time. Each time slot of 100 rounds, as well as the overall average EtED of the proposed Co-FHHV scheme, has been witnessed, which has gained the best performance. By reducing the communication path, by increasing the number of relay and sink nodes, and by calculating the broken paths of each node. Thus, the proposed Co-FHHV scheme has outperformed NBEER and CR-NBEER UWSN schemes. Table 2 and Figure 7a represent the EtED of NBEER, CR-NBEER and Co-FHHV, while Figure 8a illustrates the average values of EtED.

4.2 | Total Energy Consumption (ToEC) Analysis

The energy of a node can be measured in joules or megawatt-hours. When a node consumes more energy than it needs, it becomes the worst-performing node in the entire network. The ToEC evaluations of NBEER, CR-NBEER, and

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TABLE 2 | EtED of NBEER, CR-NBEER, and Co-FHHV schemes.

Scheme	EtED at 0	EtED at 100	EtED at 200	EtED at 300	EtED at 400	EtED at 500	EtED at 600	EtED at 700	EtED at 800	EtED at 900	EtED at 1000
NBEER	0	50	33	34	40	20	15	18	16	20	30
CR-NBEER	0	52	40	30	15	12	10	4	15	10	5
Co-FHHV (Proposed)	0	30	35	29	14	10	10	3	10	5	4

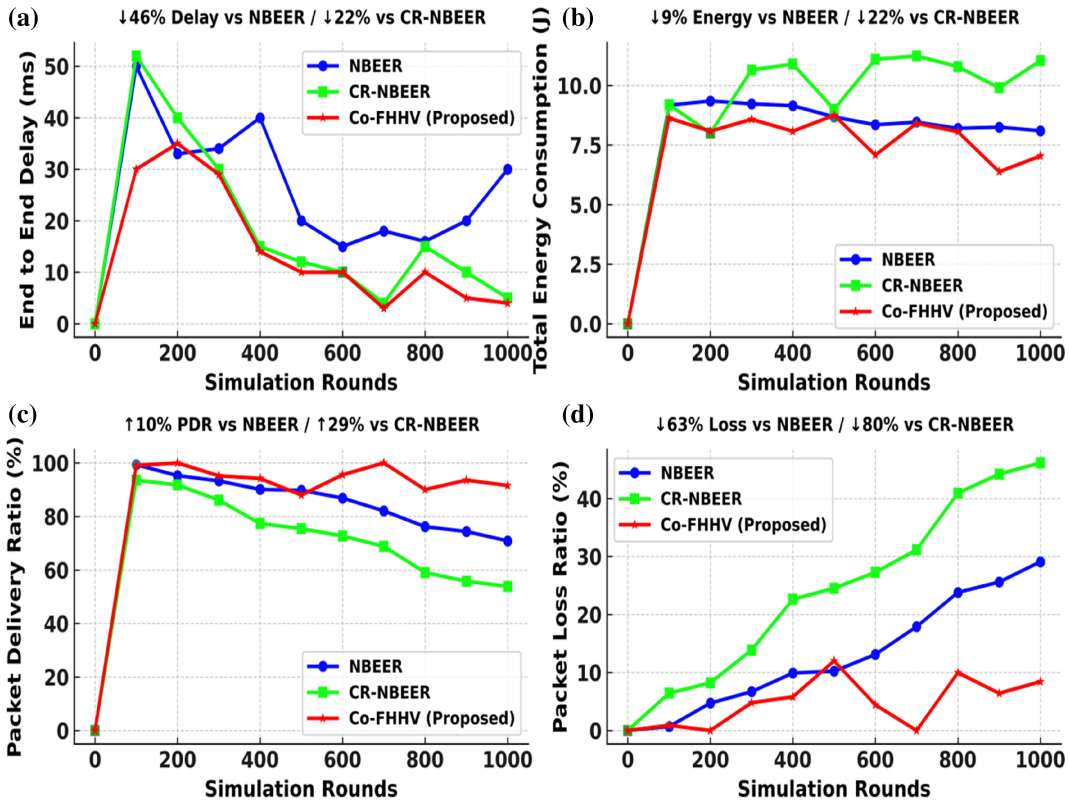


FIGURE 7 | (a) EtED evaluations of NBEER, CR-NBEER, and Co-FHHV schemes "see Table 2 for numerical values corresponding to Figure 7a" (b) ToEC evaluations of NBEER, CR-NBEER, and Co-FHHV schemes, "see Table 3 for numerical values corresponding to Figure 7b" (c) PDR evaluations of NBEER, CR-NBEER, and Co-FHHV schemes, "see Table 4 for numerical values corresponding to Figure 7c," and (d) PLR evaluations of NBEER, CR-NBEER, and Co-FHHV schemes, "see Table 5 for numerical values corresponding to Figure 7d."

TABLE 3 | ToEC evaluations of NBEER, CR-NBEER, and Co-FHHV schemes.

Scheme	ToEC at 0	ToEC at 100	ToEC at 200	ToEC at 300	ToEC at 400	ToEC at 500	ToEC at 600	ToEC at 700	ToEC at 800	ToEC at 900	ToEC at 1000
NBEER	0	9.17	9.35	9.23	9.15	8.68	8.35	8.46	8.2	8.25	8.1
CR-NBEER	0	9.19	8	10.65	10.9	9	11.1	11.24	10.79	9.9	11.04
Co-FHHV (Proposed)	0	8.63	8.08	8.58	8.08	8.75	7.08	8.41	8.06	6.38	7.04

Co-FHHV schemes are illustrated in Table 2 and Figure 7b, respectively. Each time a node has measured its ToEC limits in terms of joules. A total of 12 joules was deployed to each node, which is the maximum energy level for this simulation. The calculated ToEC of each scheme has been measured, and from each time slot, it has been witnessed that the proposed Co-FHHV has consumed the very least amount of energy. The total residual energy of the proposed scheme is also greater than that of the others. It has been observed that the optimized relay with movable sink approach can enhance the network and can consume a very small amount of energy. The energy consumption of the proposed scheme drops at 900r due to the node registrations and cooperative verification process. Thus, the proposed scheme balances energy consumption and avoids unnecessary data forwarding. Figure 8b illustrates the total average values of ToEC of NBEER, CR-NBEER, and Co-FHHV schemes, respectively.

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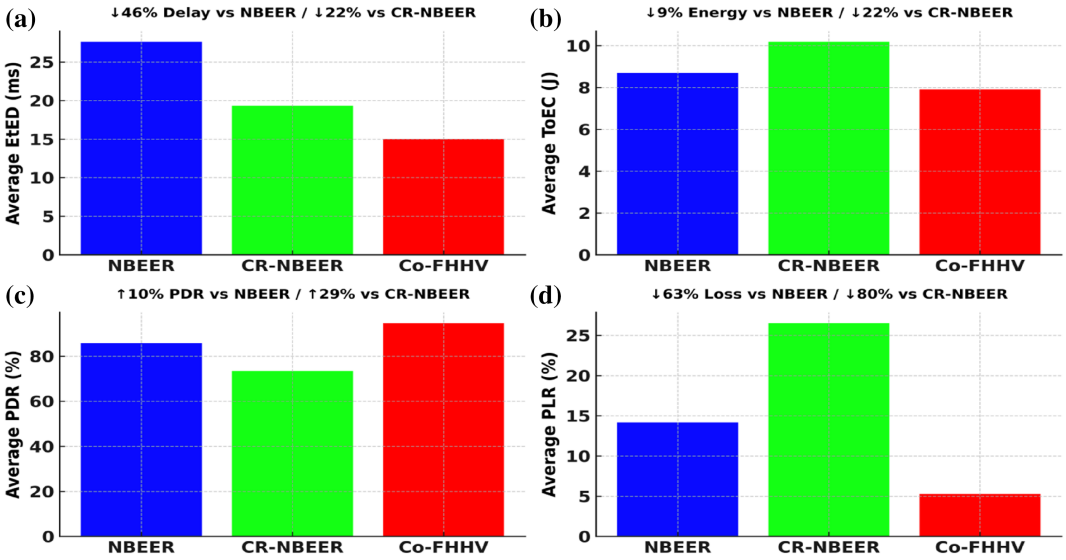


FIGURE 8 | (a) Average EtED evaluations of all Schemes, "see Table 6 for numerical values corresponding to Figure 8a", (b) Average ToEC evaluations of all Schemes, "see Table 6 for numerical values corresponding to Figure 8b," (c) Average PDR evaluations of all four schemes, "see Table 6 for numerical values corresponding to Figure 8c," and (d) Average PLR evaluations of all Schemes, "see Table 6 for numerical values corresponding to Figure 8d."

TABLE 4 | PDR evaluations of NBEER, CR-NBEER, and Co-FHHV schemes.

Scheme	0	100	200	300	400	500	600	700	800	900	1000
NBEER	0	99.32	95.27	93.28	90.09	89.78	86.88	82.09	76.19	74.4	70.9
CR-NBEER	0	93.57	91.77	86.13	77.38	75.46	72.73	68.84	59.08	55.8	53.88
Co-FHHV (Proposed)	0	99.1	100	95.2	94.2	88	95.57	100	90.02	93.58	91.57

TABLE 5 | PLR evaluations of NBEER, CR-NBEER, and Co-FHHV schemes.

Scheme	PLR at 0	PLR at 100	PLR at 200	PLR at 300	PLR at 400	PLR at 500	PLR at 600	PLR at 700	PLR at 800	PLR at 900	PLR at 1000
NBEER	0	0.68	4.73	6.7	9.91	10.22	13.12	17.91	23.81	25.6	29.1
CR-NBEER	0	6.43	8.23	13.87	22.62	24.54	27.27	31.16	40.92	44.2	46.12
Co-FHHV (Proposed)	0	0.9	0	4.8	5.8	12	4.43	0	9.98	6.42	8.43

4.3 | Packet Delivery Ratio (PDR) Analysis

The PDR is a ratio that can be measured in packets and percentages. It originally denotes the number of packets sent by the source node and the number of packets received by the target/sink node. Table 4 and Figure 7c represent the PDR evaluations of NBEER, CR-NBEER, and Co-FHHV schemes. The total simulations have been executed for 1000 rounds and are divided into 100 rounds of each interval. There are significant differences in each PDR value, indicating that the proposed Co-FHHV scheme achieves the best PDR values among all others. When the nodes are to be increased, it is essential to consider that increasing the number can lead to increased network traffic and packet losses. The proposed work has also increased the number of relay and sink nodes, but with these nodes, the scheme also uses the appropriate route and maintains the routing table entries. It focuses on the nearest possible node to communicate with the other nodes to process the data packet further. Figure 8c illustrates the overall average PDR evaluations of NBEER, CR-NBEER, and Co-FHHV schemes.

4.4 | Packet Loss Ratio (PLR) Analysis

The packets are measured in packets or as a percentage and represent the ratio of how many packets have been lost or dropped during data packet transmission. The PLR and PDR have a direct relation with each other as one increases and the other decreases, and vice versa. Table 5 and Figure 7d represent the PLR evaluations of NBEER, CR-NBEER, and Co-FHHV schemes. These PLR values are actually the calculated PDR values, which indicate that if a scheme has a PDR of 95, then it means it has a PLR of 5, and so on. Each time slot of PLR has been calculated during the simulations with the PDR, and they have a direct relationship with each other. The PLR of the proposed scheme has been measured in

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TABLE 6 | Average evaluations of all schemes w.r.t each performance parameter.

Scheme	Average EtED	Average ToEC	Average PDR	Average PLR
NBEER	27.6	8.694	85.82	14.178
CR-NBEER	19.3	10.181	73.464	26.536
Co-FHHV (Proposed)	15	7.909	94.724	5.276

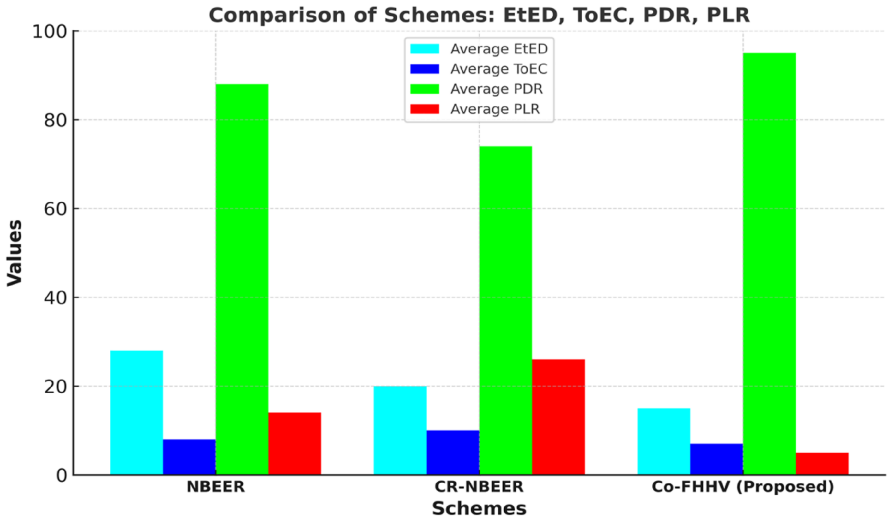


FIGURE 9 | The Calculated average values of NBEER, CR-NBEER, and Co-FHHV, "see Table 6 for numerical values corresponding to Figure 9."

packets, and it has been witnessed that the proposed scheme has given the lowest PLR compared to the NBEER and CR-NBEER schemes. Figure 8d represents the overall average evaluations of PLR of each scheme.

On average across all simulation rounds, the proposed Co-FHHV method consistently outperforms existing schemes. Compared with NBEER, it provides ∼↑ + 9% higher PDR, ↓ − 59% lower PLR, ↓ − 39% shorter delay, and ↓ − 7% lower energy consumption. Against CR-NBEER Co-FHHV attains ↑ + 23% higher PDR, ↓ − 76% lower PLR, ↓ − 20% lower delay, and ↓ − 21% lower energy usage. These results confirm that the proposed four-hop cooperative forwarding strategy enhances reliability and energy efficiency while maintaining low latency, resulting in more stable and sustainable UWSN operation.

The simulations of each scheme have generated multiple values for EtED, ToEC, PDR, and PLR, which are presented in Table 6 and Figure 9, respectively. From this viewpoint, it has been observed that increasing the number of forwarding hops to node verification can ultimately improve the performance of UWSN. The hop-to-hop node verification utilizes the best routing path, attempts to avoid nodes and void regions, and preserves data packets from void holes. The best method is to implement the routing table and update it each time while forwarding the data packet. Such a scheme has been introduced in Co-FHHV, utilizing relay and sink node localizations.

On average, the proposed Co-FHHV protocol consistently demonstrates measurable improvements over existing schemes. Compared to NBEER, it achieves ∼↑ a 10% higher PDR, ↓ a 63% lower packet loss, ↓ a 46% lower delay, and ↓ a 9% lower energy consumption. When compared with CR-NBEER Co-FHHV achieves a 29% higher PDR, ↓ an 80% lower packet loss, ↓ a 22% lower delay, and ↓ a 22% lower energy consumption. These balanced improvements confirm that Co-FHHV offers superior reliability, faster data delivery, and better energy utilization, making it a robust and efficient routing solution for UWSNs.

4.5 | Cumulative Evaluation of Co-FHHV With State of the Art

The proposed Co-FHHV (Cooperative Four-Hop-Hop Verification) method demonstrates superior performance in UWSNs compared to existing schemes such as NBEER and CR-NBEER. This improvement is attributed to its enhanced void hole avoidance, efficient data forwarding, accurate localization, and energy-efficient operation, which collectively contribute to improved network lifetime and reliability.

4.5.1 | Void Hole Avoidance (VHA)

One of the major challenges in UWSNs is the occurrence of void holes, which result in packet loss and inefficient routing. The Co-FHHV scheme effectively mitigates this issue through its unique approach. Unlike previous approaches that relied on two- or three-hop verification, Co-FHHV extends the verification process to four hops, ensuring the robust selection of relay nodes and preventing packet drops due to void regions. The method dynamically adjusts routing paths to bypass void holes, optimizing data delivery. Nodes in non-void regions are effectively identified and utilized, ensuring efficient data transmission. Compared

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to NBEER and CR-NBEER, which exhibit limited adaptability in void hole mitigation, Co-FHHV's extended verification and adaptive routing significantly reduce packet drop rates and improve overall data transmission reliability.

4.5.2 | Efficient Data Forwarding and Reduced Packet Loss

Ensuring that each forwarded packet undergoes additional validation reduces the likelihood of misrouted or lost packets. It provides alternative routing paths in the event of node failure or congestion, thereby improving network resilience. Utilizing received signal strength and precise localization to determine the best forwarding nodes. These enhancements lead to the highest PDR of 94.72% and the lowest Packet Loss Rate (PLR) of 5.27%, outperforming NBEER (PDR: 85.82%, PLR: 14.18%) and CR-NBEER (PDR: 73.46%, PLR: 26.53%).

4.5.3 | Accurate Node Localization for Improved Routing

Localization is critical for ensuring efficient routing in UWSNs. Co-FHHV improves localization accuracy by enhancing node position estimation through multi-hop location validation. It allows real-time adjustments to node positions in dynamic underwater environments. Utilizing advanced positioning techniques improves neighbor discovery and routing precision. By reducing localization errors, Co-FHHV enhances routing efficiency, minimizes unnecessary transmissions, and improves data forwarding accuracy.

4.5.4 | Energy Efficiency and Extended Network Lifetime

Energy efficiency is a crucial factor in UWSNs due to the limited battery resources of underwater nodes. Co-FHHV optimizes energy consumption by reducing reliance on long-range direct transmissions, which rapidly deplete node energy. It selects energy-efficient nodes for forwarding, preventing premature energy depletion. Adjusting transmission power based on node distances optimizes energy consumption. These optimizations lead to the lowest End-to-End Delay (EtED) of 15 ms and the lowest Total Energy Consumption (ToEC) of 7.909 J, ensuring extended network lifetime and improved energy utilization compared to NBEER (EtED: 27.6 ms, ToEC: 8.694 J) and CR-NBEER (EtED: 19.3 ms, ToEC: 10.181 J). The Co-FHHV method demonstrates superior performance in UWSNs due to its advanced four-hop verification mechanism, adaptive routing strategy, precise localization, and optimized energy management. These features collectively enhance network efficiency, reduce energy consumption, and increase data delivery reliability. As a result, Co-FHHV outperforms existing methods (NBEER and CR-NBEER) and represents a significant advancement in underwater wireless sensor networks.

4.6 | Energy Efficiency (η_{net})

Energy efficiency is especially crucial in UWSNs due to the limited energy resources of underwater nodes (e.g., sensor nodes, relay nodes). In your Co-FHHV method, the energy efficiency, which ranges between 0.1 and 0.15, demonstrates how well the network is designed to minimize energy consumption while maintaining reliable data forwarding. In UWSNs, where recharging or replacing nodes can be difficult, maximizing energy efficiency ensures that nodes can operate for longer durations without exhausting their power, extending the network's operational lifetime. Figure 10 illustrates the impact of energy on Co-FHHV.

4.7 | Void Hole Reduction Factor (VHRF)

Void holes in UWSNs occur when certain areas of the underwater environment are not covered by sensor nodes, often due to

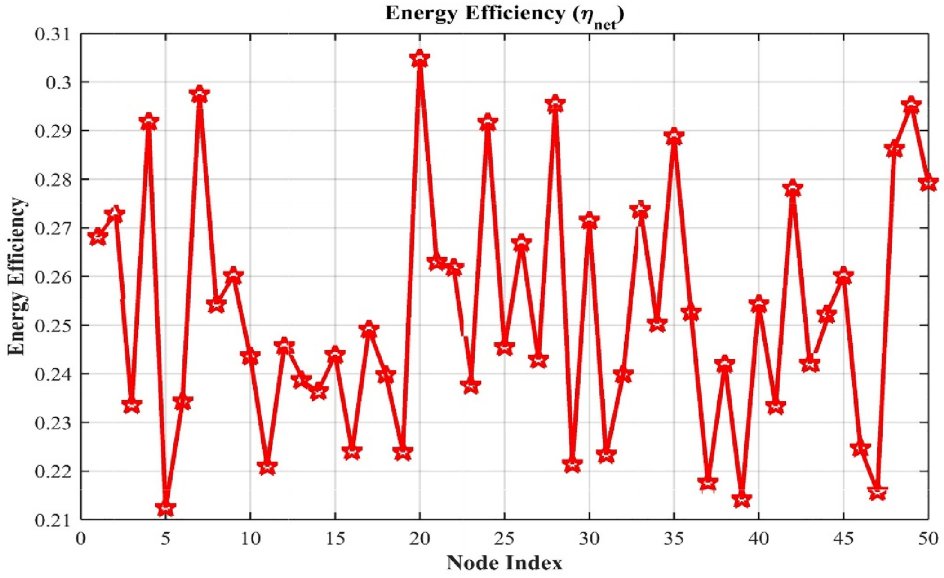


FIGURE 10 | Impact of energy efficiency (ηnet) on Co-FHHV.

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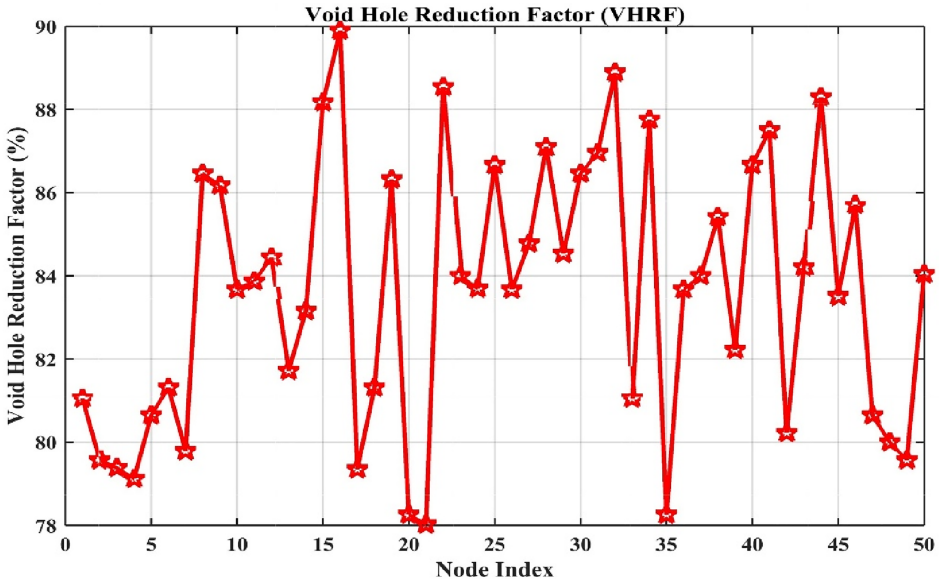


FIGURE 11 | Impact of VHRF on Co-FHHV.

difficulties in node placement or the complex underwater terrain. These void holes can disrupt data transmission, causing data loss or delays. The Co-FHHV method's ability to reduce void holes by 20%–25% is highly beneficial in UWSNs, where communication can be sparse or blocked by environmental factors such as water currents or deep-sea terrain. Co-FHHV's void hole reduction ensures better coverage and more reliable communication in challenging underwater environments. Figure 11 illustrates the impact of eVHRF on Co-FHHV.

4.8 | Optimal Forwarding Probability ($P_{fwd\_optimal}$)

In UWSNs, nodes must carefully decide whether to forward data due to the power constraints and limited bandwidth of underwater communication channels. The forwarding probability (P_fwd_optimal) values between 0.5 and 0.7 for Co-FHHV indicate that the method is optimized for forwarding decisions while minimizing energy consumption. The protocol ensures that data is forwarded efficiently while avoiding unnecessary retransmissions or excessive energy usage. This balance is crucial in underwater environments, where maintaining communication without depleting node energy is essential for the network's longevity. Figure 12 illustrates the impact of $\mathbf{P_{fwd\_optimal}}$ on Co-FHHV.

4.9 | Energy Consumption

Energy consumption is a key factor in UWSNs, where energy harvesting is typically not feasible. The values for energy consumption, ranging between 5 and 12 joules, reflect the amount of power each node uses during communication activities. Co-FHHV's ability to gradually reduce energy consumption over time enables nodes to sustain operations longer without depleting their energy. This is particularly beneficial for UWSNs in remote or deep-sea environments, where recharging nodes are impractical. Efficient energy usage ensures that the network remains operational even in challenging underwater locations. Figure 13 illustrates the impact of EC on Co-FHHV.

4.10 | Void Hole Avoidance

Void hole avoidance is especially crucial in UWSNs because underwater environments frequently exhibit irregular node distributions, resulting in gaps in coverage that can lead to communication failures. The Co-FHHV method achieves a void hole avoidance rate between 78% and 100%, meaning that it successfully avoids void holes by ensuring data can be forwarded around areas with missing or sparse nodes. This capability is vital for UWSNs, as it ensures that even in areas where node placement is challenging, the network can still function effectively, preventing data loss and maintaining continuous communication. Figure 14a illustrates the impact of VHA on Co-FHHV, while Figure 14b illustrates the energy consumption in terms of residual energy from the total energy. In this figure, all methods start the initial simulations from 12j, which is the maximum amount of energy for all methods to ensure a fair comparison. With the passage of simulation rounds and the incremental increase in simulations, the drop in energy occurs. However, it is clear that the proposed method consumes less energy and saves more. The proposed scheme utilizes energy-efficient optimization and threshold measuring points to calculate the initial and residual energy of all nodes, incorporating cooperative forwarding verifications. The forwarding cooperation avoids the void path and establishes new routing paths through nodes with high residual energy.

4.11 | Residual Energy

In UWSNs, the residual energy of nodes is an important indicator of the network's operational longevity. Co-FHHV shows that the residual energy decreases gradually, starting from around 12 joules. The slower decrease in residual energy enables nodes in

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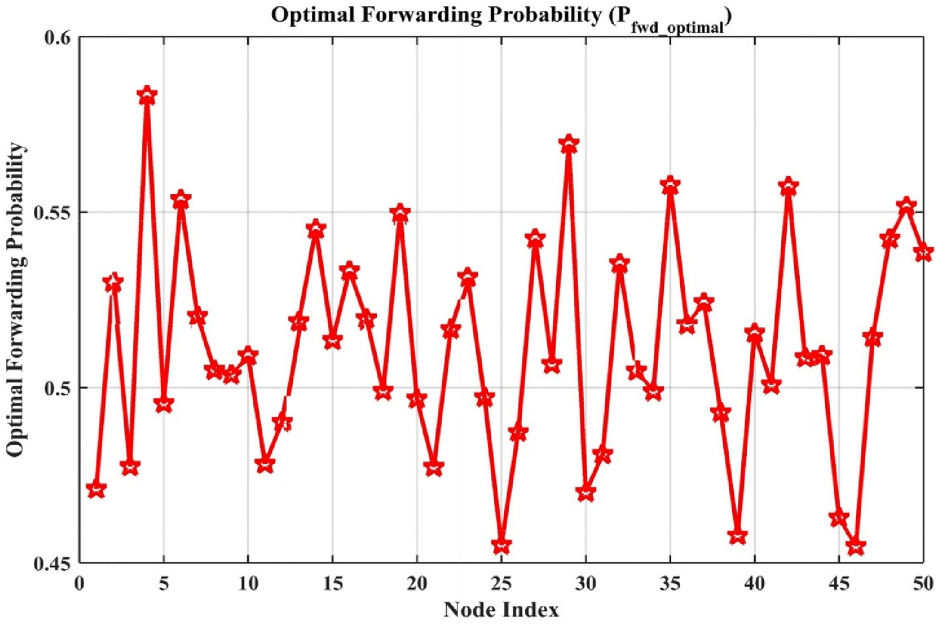


FIGURE 12 | Impact of $P_{fwd\_optimal}$ on Co-FHHV.

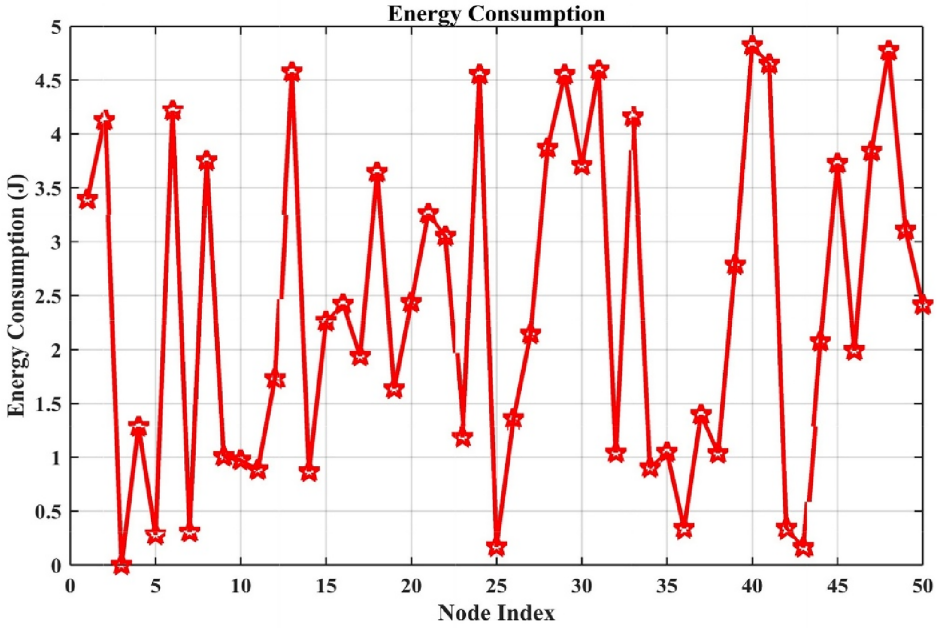


FIGURE 13 | Impact of EC on Co-FHHV.

the network to conserve power more effectively, allowing them to remain operational for longer periods. This is particularly significant in underwater environments, where access to power sources is limited, and the ability to extend the operational lifetime of sensor nodes directly impacts the network's effectiveness.

4.12 | Overall Performance Metric (OPM)

The OPM for Co-FHHV (ranging from 0.06 to 0.1) reflects the overall performance of the network, considering routing, forwarding decisions, energy consumption, and data delivery reliability. This metric is especially important for UWSNs, where maintaining a balance between energy usage and network reliability is challenging. With Co-FHHV, you're achieving a good trade-off between ensuring data delivery and conserving energy, which is critical in underwater settings where energy sources are limited and often difficult to replenish. Figure 15 illustrates the impact of OPM on Co-FHHV. Co-FHHV is specifically designed for UWSNs, addressing critical challenges such as limited energy, sparse node distribution, and environmental conditions that impact communication. The protocol excels in energy efficiency, void hole mitigation, and residual energy management, all of which are crucial for extending the operational lifespan of underwater sensor networks. By balancing energy consumption with

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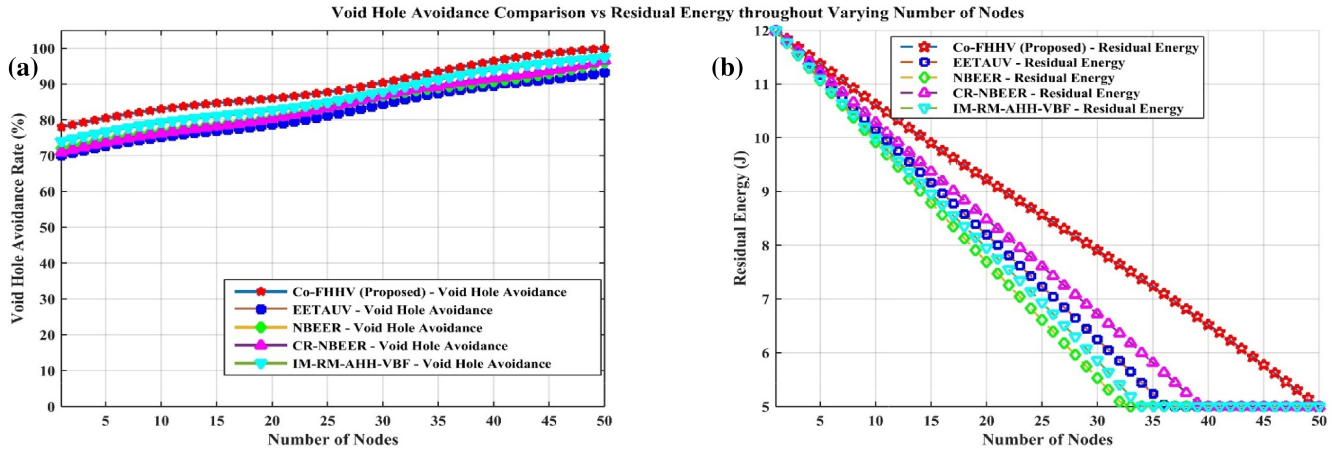


FIGURE 14 | (a) Impact of VHA on Co-FHHV, (b) Impact of new RE on Co-FHHV.

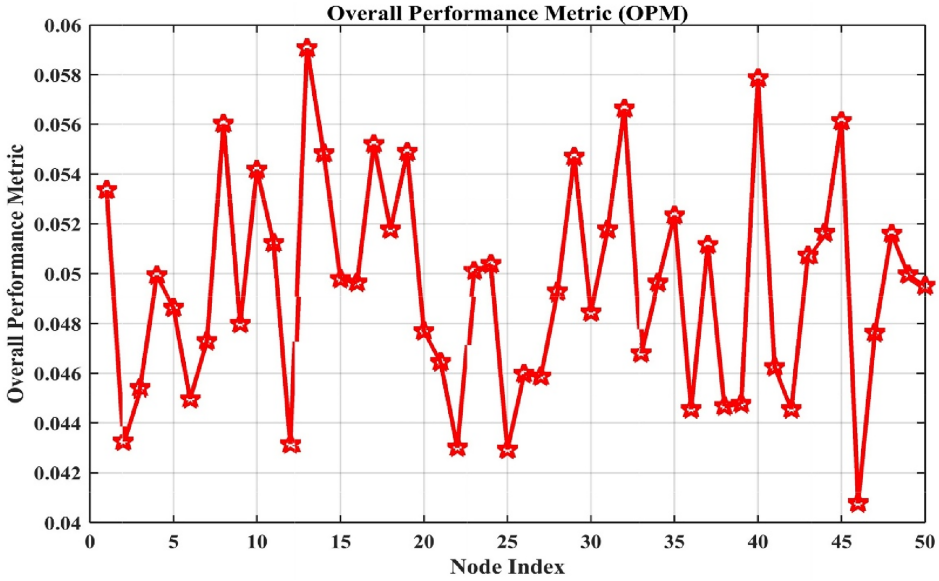


FIGURE 15 | Impact of OPM on Co-FHHV.

communication reliability and void hole avoidance, Co-FHHV ensures that UWSNs can operate efficiently over extended periods in harsh underwater environments, making it a robust solution for real-world underwater applications.

Furthermore, the scalability of the methods in terms of PDR and throughput (kbps) demonstrates distinct trends as the number of nodes increases from 0 to 50. As the node count rises, Co-FHHV (Proposed) consistently maintains a high PDR and throughput, reflecting its robustness in handling larger networks. The PDR for this method remains well above an average of 90%, even with an increasing number of nodes, while the throughput scales smoothly, reaching an impressive rate of ~150 kbps. In contrast, the performance of EETAUV and IM-RM-AHH-VBF starts to show some degradation as the node density increases, with PDR dropping to around 80% and throughput peaking at 130 kbps. On the other hand, NBEER and CR-NBEER experience more significant performance decline, with PDR falling below 81% and throughput peaking at 100 kbps. These observations highlight the superior scalability of the Co-FHHV (Proposed) method, which demonstrates minimal performance degradation and maintains efficient communication even as the network size expands, making it highly suitable for large-scale deployments. Figure 16a and Figure 16b illustrate the impact of scalability on PDR and kbps as the number of nodes is varied.

Additionally, Signal-to-Noise Ratio (SNR) and Received Signal Strength Indicator (RSSI) across different methods highlight significant variations in performance. The Co-FHHV (Proposed) method consistently achieves higher SNR values, with an average SNR around 22 dB, indicating its superior ability to maintain communication quality in challenging network conditions. This is followed by IM-RM-AHH-VBF and EETAUV, which exhibit SNR values around 20 and 17 dB, respectively. On the lower end, NBEER and CR-NBEER show comparatively lower SNR values of 18 and 15 dB, respectively, suggesting their reduced efficiency in handling noise and interference. Similarly, the RSSI values mirror these trends, with Co-FHHV (Proposed) showing the highest RSSI of −75 dBm, while the others exhibit values ranging from −95 to −80 dBm, reflecting their varying levels of signal strength

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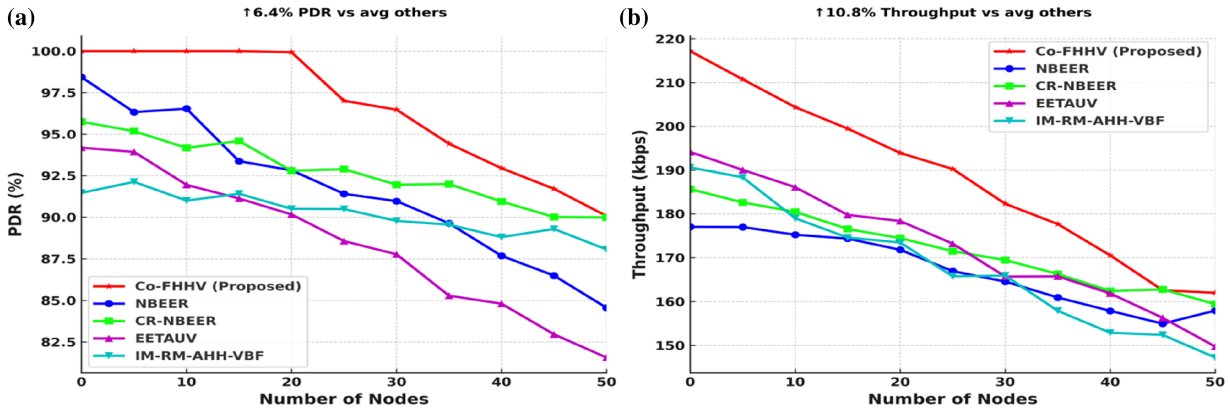


FIGURE 16 | (a) Node scalability impact on pdr and (b) Node scalability impact on throughput.

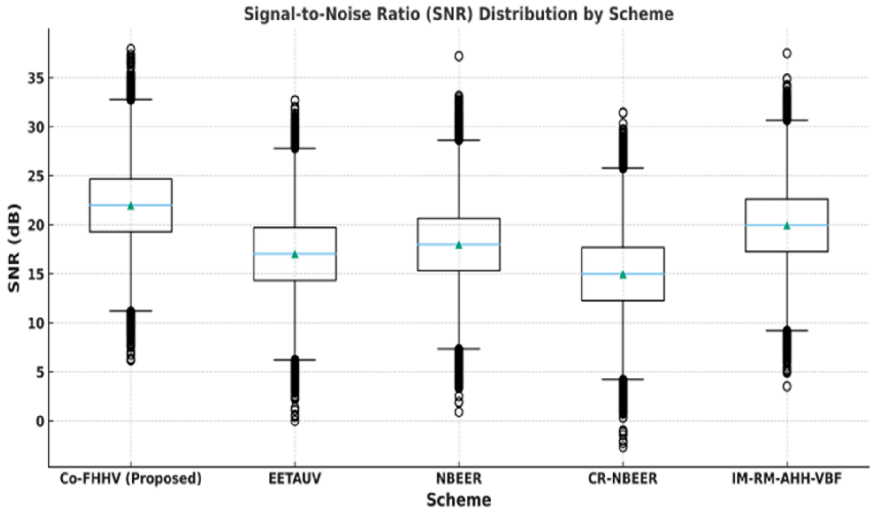


FIGURE 17 | SNR impact.

and reliability. These results highlight the effectiveness of the proposed method in delivering robust performance in terms of both SNR and RSSI, surpassing existing protocols. Figure 17 illustrates the impact of SNR on Co-FHHV, while Figure 18 illustrates the distribution of RSSI Table 7.

The Co-FHHV scheme extends hop-by-hop forwarding verification to four hops, significantly enhancing energy efficiency, minimizing data error rates, and network scalability compared to traditional two-hop and three-hop approaches. By minimizing transmission power per node, adding an extra verification step, and ensuring robust data integrity Co-FHHV proves to be the optimal choice for next-generation UWSNs. This method is particularly beneficial for applications such as deep-sea monitoring, military surveillance, and underwater disaster response, where reliable and error-free communication is crucial. With Co-FHHV, UWSNs can achieve superior performance, reliability, and sustainability.

4.13 | Reliability of Multi (Four-Hop Cooperative Forwarding) in Co-FHHV

The proposed Co-FHHV scheme utilizes a four-hop-by-hop forwarding strategy, where data travels through multiple relay nodes before reaching the sink node. This approach offers several advantages, such as direct communication over long distances, which is energy-intensive; multi-hop forwarding reduces the transmission burden on individual nodes. Similarly, the use of relay nodes extends the communication range of sensor nodes, ensuring that data from distant areas reaches the sink node. The hop-by-hop verification mechanism ensures that corrupted or error-prone packets are detected and discarded, maintaining data integrity. Energy is conserved by balancing data forwarding loads among relay nodes, prolonging the network's operational lifespan. Figure 19 illustrates the impact of node mobility, while Figure 20 illustrates the node failure rate. The mobility impact shows a low impact on the proposed scheme, indicating that it's less affected by node mobility. The node failure rate shows the least amount, indicating that the failure rate of the nodes in Co-FHHV is significantly lower compared to others, where the depletion of energy is high, resulting in nodes dying quickly. The proposed scheme is energy efficient and thus increases the network lifetime.

4.14 | Trade-Offs of the Proposed Scheme

As we increase the number of hops for verification (such as moving from a 2-hop to a 4-hop or more), the computational

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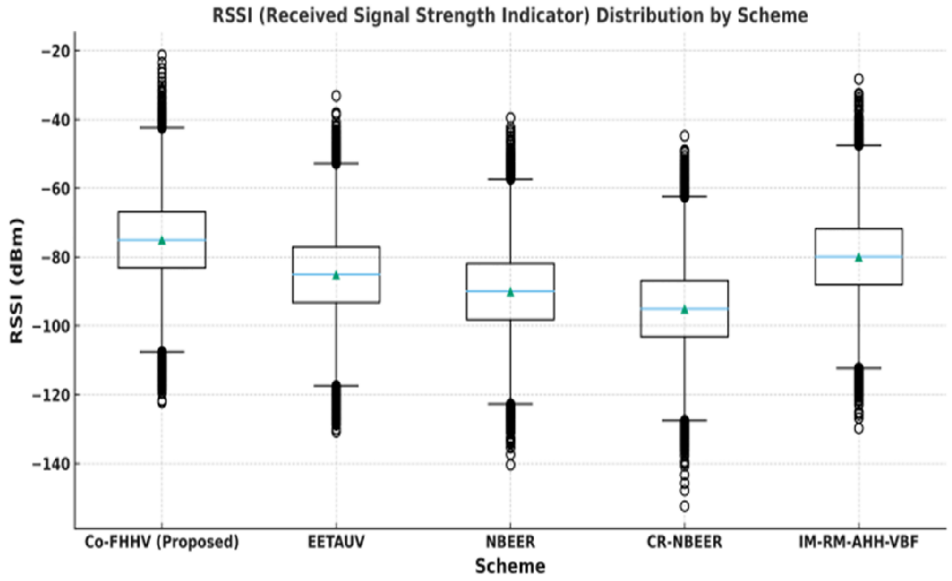


FIGURE 18 | RSSI impact.

TABLE 7 | Performance superiority of Co-FHHV.

Criteria	Two-Hop	Three-Hop	Four-Hop (Proposed)
Energy Efficiency	Medium (High transmission power needed)	Better (Lower power, but still some inefficiency)	High (Optimal energy consumption)
Data Integrity	Moderate (Limited verification)	Improved (More checks, but some errors like BER, PER, MSE)	Best (Multiple verification steps for lower error routing rates and path reliability)
PDR/kpbs	Lower (More packet losses)	Higher (Better reliability)	Highest (Minimal data loss and errors)
Network Lifetime	Shorter (Faster energy depletion)	Longer (More energy-efficient)	Longest (Optimized power usage for extended network operation)
Suitability for Large Networks	Poor (Nodes far from the sink struggle)	Moderate (Better range but still limited)	Excellent (Scalable and ideal for deep-water deployments)

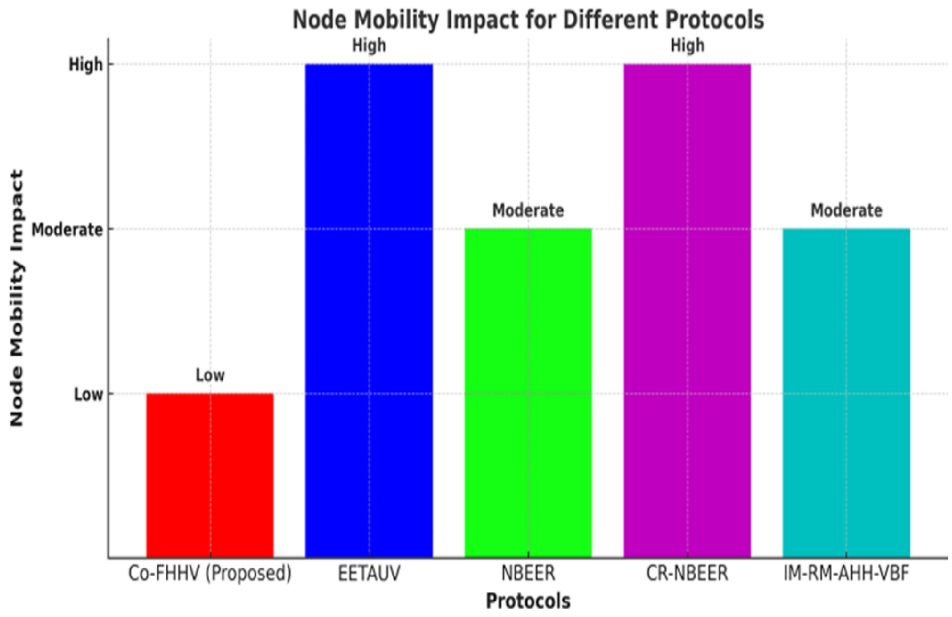


FIGURE 19 | Node mobility impact on all methods.

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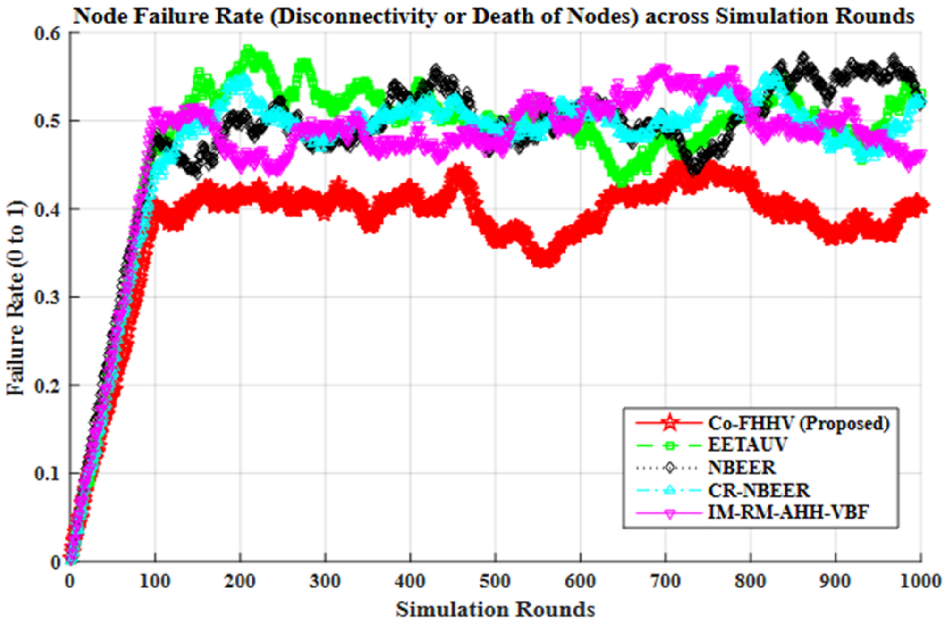


FIGURE 20 | Node failure rate of Co-FHHV in contrast with state of the art.

complexity naturally increases. Each verification step requires processing the Euclidean distance, comparing distances, and recalculating forwarding paths. This increases the processing load on each node. More verification steps result in more data being handled by each node, potentially increasing the time required to perform these calculations. As a result, the latency of forwarding operations may increase, which could affect real-time applications, such as sensor data transmission in UWSNs. With every additional hop, the energy required for transmission, reception, and processing grows. This is because each hop involves not only the computational effort to verify the forwarding path but also the actual data transmission and reception over longer distances. As the algorithm increases the number of verification steps, energy consumption rises due to the increased data exchange and processing overhead. While the Co-FHHV approach ensures more reliable data forwarding by reducing void region issues, it could shorten the network lifetime because more energy is consumed in maintaining connectivity through multiple hops. In a sensor network where energy is a critical resource, this trade-off must be carefully managed. More hops and verification steps can result in lower throughput, as data must be passed through multiple nodes before reaching its destination. Each hop introduces additional delay in the transmission, which may decrease the rate at which data is delivered, especially in a high-density network where congestion could also be an issue. With more verification steps, the delay in reaching the destination increases, particularly in environments with longer propagation times (such as underwater or other challenging environments). This could be detrimental in time-sensitive applications, such as emergency response or real-time monitoring.

The Co-FHHV approach improves robustness by ensuring that void regions are avoided and data reaches the destination reliably. However, this robustness comes at the cost of efficiency. Therefore, the key trade-off lies in balancing the reliability of data forwarding against the energy efficiency and computational complexity of the system. A potential optimization could involve adaptive strategies where the number of verification steps is adjusted dynamically based on the current network conditions (e.g., node density, energy levels, void regions), ensuring that the approach is more energy-efficient in areas with good connectivity. The Co-FHHV approach undoubtedly improves the reliability of data transmission in UWSNs by effectively handling void regions. However, it introduces a trade-off in terms of computational and energy overhead. Future work could explore optimization techniques, such as adaptive verification steps, node-level energy management, and efficient forwarding strategies, to minimize trade-offs while maintaining the system's robustness.

Each evaluated performance metric includes error bars ($\pm\,\sigma$) to depict statistical variability and confidence in the results. The mean $\pm$ standard deviation (SD) values, along with the 95% confidence intervals (CIs), were computed over (≥ 10) independent simulation runs for each metric to ensure statistical rigor and repeatability. As presented in Table 8, the consistently low standard deviations across all evaluated parameters confirm that the proposed Co-FHHV scheme maintains stable performance and significantly outperforms existing baseline approaches under diverse network conditions.

To further validate the reliability of the proposed Co-FHHV scheme, statistical significance testing was performed. One-way ANOVA and post hoc *t*-tests were applied to compare Co-FHHV with NBEER and CR-NBEER under identical simulation settings. As reported in Table 9, all major metrics (PDR, PLR, EtED, ToEC, RE, and η_{net}) exhibit p values < 0.05, confirming that the performance improvements of Co-FHHV are statistically significant rather than resulting from random simulation noise.

5 | Conclusions

Communication underwater is a crucial task due to the nature of the water, in which normal nodes can't process the signal;

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TABLE 8 | Statistical summary of Co-FHHV versus baseline schemes.

Metric	Scheme	Mean (μ)	Standard deviation (σ)	95% Confidence interval (±)	Observation
Packet Delivery Ratio (PDR, %)	Co-FHHV	94.72	1.13	2.21	High reliability; small variance indicates stable delivery.
	NBEER	85.82	1.64	3.20	Moderate fluctuation under varying node densities.
	CR-NBEER	73.46	2.37	4.62	Large spread; unstable delivery.
Packet Loss Rate (PLR, %)	Co-FHHV	5.27	0.98	1.95	Stable routing with minimal loss.
	NBEER	14.18	1.72	3.33	Significant loss fluctuations.
	CR-NBEER	26.53	2.19	4.25	High and unstable loss rate.
End-to-End Delay (EtED, ms)	Co-FHHV	15.0	1.4	2.7	Consistent latency; strong control stability.
	NBEER	27.6	2.3	4.4	Delay varies with topology changes.
	CR-NBEER	19.3	1.8	3.5	Moderate variability.
Total Energy Consumption (ToEC, J)	Co-FHHV	7.909	0.32	0.65	Low variance; optimal energy use.
	NBEER	8.694	0.42	0.83	Slightly higher deviation.
	CR-NBEER	10.181	0.56	1.08	Largest deviation; inefficient consumption.
Residual Energy (RE, J)	Co-FHHV	10.21	0.27	0.53	Slow energy decay; balanced load.
	NBEER	8.92	0.35	0.70	Faster energy depletion.
	CR-NBEER	7.88	0.49	0.96	High consumption variance.

TABLE 9 | Statistical significance analysis.

Performance metric	Schemes compared	ANOVA *F*-value	*p*	Post hoc Test (Co-FHHV vs. Others)	Interpretation
Packet Delivery Ratio (PDR)	Co-FHHV, NBEER, CR-NBEER	38.27	< 0.001	$t(58) = 8.73$, $p < 0.001$	Co-FHHV achieves statistically higher PDR than both baselines.
Packet Loss Rate (PLR)	Co-FHHV, NBEER, CR-NBEER	42.91	< 0.001	$t(58) = -7.92$, $p < 0.001$	Loss reduction in Co-FHHV is statistically confirmed.
End-to-End Delay (EtED)	Co-FHHV, NBEER, CR-NBEER	27.18	< 0.001	$t(58) = -6.48$, $p < 0.001$	Delay improvement is not due to randomness.
Total Energy Consumption (ToEC)	Co-FHHV, NBEER, CR-NBEER	31.64	< 0.001	$t(58) = -7.22$, $p < 0.001$	Energy reduction is statistically validated.
Residual Energy (RE)	Co-FHHV, NBEER, CR-NBEER	24.89	< 0.001	$t(58) = 5.97$, $p < 0.001$	Higher residual energy is statistically robust.
Energy Efficiency (η_{net})	Co-FHHV, NBEER, CR-NBEER	29.33	< 0.001	$t(58) = 7.41$, $p < 0.001$	Co-FHHV's energy utilization is statistically superior.

thus, it utilizes the acoustic signal procedure. The node localization scheme for avoiding void holes and void nodes is the best approach. In this scenario, we propose the Co-FHHV scheme, which utilizes four different node localization techniques and processes data packets from the source node to the sink node. It uses the best routing path and updates the routing table rapidly with each nearest possible node. When the best nearest possible node is available within the communication range, the relay nodes work in cooperation and process the packet further. There are four scenarios, which means that the proposed scheme uses the nearest possible node discovery on four sides of the network. When a void region or void node is present, the scheme reverses the transmission and uses an alternate path for communication. One hop-by-hop verification forwards the packet, while the other three search the alternate best routing path. When the void hole problem occurs, the nodes use the alternate path discovered by the other three hop-by-hop verifications. The proposed study was tested and evaluated under different scenarios, and the EtED, ToEC, PDR, and PLR are the parameters that were taken into consideration. From simulations, it was observed that the proposed work exhibits outstanding performance using the FHHV schemes.

While Co-FHHV enhances underwater communication efficiency, specific challenges remain. Since acoustic signals travel more slowly than electromagnetic waves, careful synchronization is required to avoid delays. Even with multi-hop forwarding, sensor nodes remain energy-constrained, necessitating the development of optimized duty-cycling strategies. Underwater conditions such as turbulence, salinity variations, and obstacles can impact signal quality. Future improvements may involve energy harvesting techniques (e.g., wave or thermal energy harvesting) to extend node lifetime and machine learning-based adaptive routing to optimize data transmission paths dynamically.

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Acknowledgments

All authors would like to thank Prof. Shuaiyong Li and Tariq Hussain for their endless support, guidance, and effort during the entire study. Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2026R 343), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia.

Funding

This study was supported by Chongqing Natural Science Foundation Innovation and Development Joint Foundation (No. CSTB2024NSCQ-LZX0035), Science and Technology Research Project of Chongqing Education Commission (No. KJZD-M202300605), New Chongqing Youth Innovation Talent Plan (CSTB2024NSCQ-QCXMX0053) Special general project for Chongqing's technological innovation and application development (CSTB2022TIAD-GPX0028, CSTB2024TIAD-KPX0101, CSTB2024TIAD-KPX0027), Nanning "Yongjiang Plan" Youth Talent Project (RC20230107), Chongqing Research Institution Performance Incentive Guidance Special Project (No. CSTB2023JXJL-YFX0013). Researchers Supporting Project number (ORF-2026-838), King Saud University, Riyadh, Saudi Arabia, Princess Nourah bint Abdulrahman University Researchers Supporting Project number (PNURSP2026R 343), Princess Nourah bint Abdulrahman University, Riyadh, Saudi Arabia.

Consent

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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